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Mission-Related Design Requirements for the LEM Environmental Control Subsystem

Apollo Mission Planning Task Force

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1. SUMMARY

The purpose of this document is to define the mission-related critical design requirements for the LEM Environmental Control Subsystem (ECS) and to examine the present subsystem capabilities relative to these requirements for both nominal and contingency situations.

A description of the subsystem is provided and the functional requirements of the ECS are stated. Briefly, the functional requirements consist of oxygen supply and cabin pressure control, atmosphere revitalization, thermal control, water management, and PLSS re-charge.

It was concluded that the LEM design should, and indeed essentially does provide the flexibility for either:

- Maximum stay (up to 45 hours) on the lunar surface within the constraints of a 48 hour separated LEM life.

or

- A lunar stay of approximately 35 hours plus provisions for a nine hour orbital contingency in addition to the normal ascent requirements.

To provide the capability for additional surface explorations during extended lunar stays up to 45 hours, the following recommendations were made:

- Provide for a total of 28 man-hours of PLSS operation, of which 24 man-hours are allotted for lunar surface exploration.
- Provide for nine LEM cabin repressurizations. Repressurizations to 3.7 ± 0.2 PSIA would be acceptable when one astronaut is out on the lunar surface.
- Carry an extra PLSS battery on board the LEM.

There is sufficient oxygen stored aboard the LEM to provide nine cabin repressurizations (see Reference 4), but two extra PLSS lithium hydroxide cartridges would be required to meet the critical design requirements for extra-vehicular operations.

The possibility of transferring water from the CSM to the LEM was investigated and is believed to be a feasible way of reducing the earth launch weight. It is recommended that this subject be given further consideration.

2. LEM ENVIRONMENTAL CONTROL SUBSYSTEM DESCRIPTION

The Environmental Control Subsystem (ECS) consists of five integrated sections: atmosphere revitalization, oxygen supply and cabin pressure control, heat transport, water management, and cold plate (See Figure 1). The major portion of the ECS equipment is in the pressurized compartment of the ascent stage. A glycol loop and a gaseous oxygen accumulator are in the ascent stage equipment bay section. Two water tanks are in the tankage section of the ascent stage, while a third (larger) water tank is in the descent stage.

The ECS controls the oxygen in, pressurization of, ventilation of, and temperature of the cabin and the space suits worn by the two astronauts. It provides oxygen for the astronaut's space suits, cabin, and Portable Life Support System (PLSS); it limits the level of carbon dioxide and removes odors, moisture, and particulate matter from the oxygen breathed by the crew; and it automatically controls the temperature of the electronic equipment. The ECS also stores water for drinking, food preparation, and the PLSS.

2.1 ATMOSPHERE REVITALIZATION

The atmosphere revitalization section consists of a suit circuit assembly and cabin recirculation assembly which conditions the oxygen for cooling and ventilating the space suits worn by the crew and monitors cabin oxygen recirculation and temperature. More specifically, the suit circuit assembly controls the carbon dioxide level of the atmosphere breathed by the crew, removes odors and noxious gases from the crew atmosphere, removes particulate matter within the space craft, removes excess moisture from the cabin atmosphere, and provides control of the space suit gas temperature and the gas flow through the space suits.

The suit circuit assembly consists of two (one redundant) suit circuit fans, a suit circuit heat exchanger and water evaporator, and two (one redundant) water separators. In addition, the section contains a regenerative heat exchanger, a carbon dioxide partial pressure sensor, two carbon dioxide odor removal canisters, relief valve, check valves and interconnecting tubing.

Oxygen from the oxygen supply and cabin pressure control section is circulated through the suit circuit assembly section by one of the two redundant suit circuit fans. As either of the fans can maintain the required suit-circuit oxygen flow, only one fan is operated at a time. After leaving the fan, the oxygen passes through the suit circuit heat exchanger, which transfers excess heat from the oxygen to the heat transport section coolant. The suit circuit water evaporator removes the excess heat in the event of failure of the suit circuit heat exchanger. Moisture that condenses when the oxygen passes through the suit circuit heat exchanger or suit circuit water evaporator is removed from the oxygen by one of the two redundant water separators. Each separator can meet the water removal requirements but depending on the position of the manually operated water separator selector valve, only one of the separators will function at a time.

Downstream from the two water separators is the suit circuit regenerative heat exchanger, which allows the temperature of the oxygen to be manually controlled by the crewmember before it enters the space suits. Warm coolant from the heat transport section flows through the heat exchanger, transferring heat to the oxygen. The temperature of the oxygen is controlled by varying the flow of coolant through the heat exchanger; the astronaut manually controls this flow by the suit temperature control valve.

In addition, the astronauts control their comfort by their individual flow control valve. The carbon dioxide partial pressure sensor monitors the carbon dioxide partial pressure level. The oxygen then passes through one of the two redundant carbon dioxide and odor removal canisters, each consisting of a canister and replaceable cartridge, and once again flows into one of the two suit circuit fans where the cycle is repeated.

During open-faceplate operation (normal pressurization level), the suit-circuit diverter valve is opened to pass the entire oxygen flow from the suit circuit assembly into the cabin. This ensures that a sufficient amount of cabin oxygen is circulated through the suit circuit assembly to maintain the desired carbon dioxide and humidity levels in the cabin. In the event of a decompression of the cabin atmosphere, the cabin pressure switch provides a signal that automatically closes the diverter valve. The suit-circuit relief valve prevents over-pressurization of the assembly. When the pressure is 4.4 psia or greater, the relief valve is fully open; when the pressure is less than 4.1 psi, the relief valve is fully closed.

Recirculation and temperature control of the cabin oxygen is provided by the cabin recirculation assembly. The assembly contains fans that recirculate the oxygen and a cabin heat exchanger that automatically heats or cools the oxygen. Heat is transferred between the cabin gas and heat transport section coolant that flows through the cabin heat exchanger. The temperature of the coolant is controlled in the heat transport section.

2.2 OXYGEN SUPPLY AND CABIN PRESSURE CONTROL

The oxygen supply and cabin pressure control section provides oxygen required by the atmosphere revitalization section and also supplies oxygen to refill the PLSS, used during exploration of the lunar surface. In addition, the section maintains cabin pressure by supplying oxygen at a rate equal to cabin leakage plus crew consumption, allows for cabin depressurization and subsequent pressurization by the astronauts and maintains space suit pressure during unpressurized cabin operation.

The oxygen supply and cabin pressure control section consists of a gaseous oxygen accumulator, two (one redundant) oxygen demand regulators, various check valves, shutoff valves and interconnecting tubing.

At the normal pressurization level, the pressure in the cabin and the space suits is maintained at 5 ± 0.2 psia, which permits the astronauts to open their faceplates and remove their gloves. With the cabin depressurized, the space suits must be sealed and the pressure in the suits is reduced to the egress mode level of $3.7^{+.02}_{-.00}$ psia.

The oxygen stored in the supercritical storage assembly is sufficient for the required cabin repressurizations and refills of the PLSS primary oxygen storage tanks, in addition to normal crew consumption and vehicle and space suit leakage. The gaseous oxygen accumulator is used in conjunction with normal oxygen flow for cabin repressurizations that require high oxygen flow rates. The self-sealing PLSS oxygen disconnect permits refilling the PLSS primary oxygen storage tanks.

Pure oxygen from the supercritical storage assembly in the descent stage passes through one of the cryogenic oxygen heat exchangers where it is warmed by the heat transport section coolant to make it compatible with the operation of components in the oxygen supply and cabin pressure control section and the atmosphere revitalization section. Two oxygen demand regulators (one redundant), each with a manual override control the delivery

of oxygen to the atmosphere revitalization section in response to signals from pressure sensors. The cabin repressurization and emergency oxygen valve supplies oxygen to the cabin for cabin repressurization or to slow the loss of cabin pressure in the event of punctures in the cabin pressure shell, in response to signals from the cabin pressure switch. In addition, the valve has a manual override.

Overpressurization of the oxygen supply and cabin pressure control section is prevented by the oxygen pressure relief valve, which automatically relieves excess pressure by venting oxygen into the cabin. Overpressurization of the cabin is prevented by the cabin pressure relief and dump valves which automatically relieves excess cabin pressure by venting oxygen overboard or can be manually operated, from inside or outside the cabin, to dump the cabin pressure overboard.

2.3 HEAT TRANSPORT

The heat transport section of the LEM consists of two closed-loop systems - the primary and the secondary. Each of these systems circulates an ethylene glycol-water coolant to provide temperature control of the electronic equipment. In addition, the primary system provides temperature control of the oxygen circulated through the cabin and the space suits and warms the cryogenically stored oxygen and hydrogen.

The primary coolant loop consists of two coolant pumps (one redundant), the cabin temperature control valve, coolant regenerative heat exchanger, Freon boiler, coolant water evaporator, coolant accumulator, coolant filter, various valves, and interconnecting tubing. The secondary coolant loop, used for cooling of critical equipment in the event of primary system failure, consists of a coolant pump, coolant water evaporator, filter, valves, and interconnecting tubing.

In the primary coolant loop, the coolant is circulated by one of the two coolant pumps. Each pump can provide normal flow and only one pump is operated at a time. After leaving the pump, the coolant flow divides, some going through the suit-circuit heat exchanger to transfer the heat from the oxygen to the coolant and some going through part of the cold plate section where it absorbs heat from the electronic equipment. The flow then divides between the regenerative heat exchanger and its bypass obtaining the required heat for the cabin heat exchanger from the regenerative heat exchanger.

The flow split is made by the cabin temperature control valve which is controlled by the cabin heat exchanger glycol-water discharge temperature. The cabin heat exchanger discharge coolant temperature is maintained within a narrow range of temperature which in turn maintains the heat exchanger discharge temperature and cabin temperature within the required limits.

The coolant then passes through another parallel cold plate section where it receives waste heat from the electronic equipment. After passing the cold plate section, the flow is controlled to the suit circuit regenerative heat exchanger for suit heating by the suit temperature control valve. Warm coolant then flows in parallel paths through the cryogenic oxygen and hydrogen heat exchangers to warm the oxygen and hydrogen supplied from the supercritical storage assemblies. Waste heat is removed from the coolant in the water evaporator by a sublimation process and its products discharged overboard. The coolant then flows through the coolant filter (which removes particles that could cause a malfunction) and into the coolant pumps continuing the cycle. The coolant accumulator maintains pressure above the coolant vapor pressure in the heat transport section and accommodates volumetric changes of the coolant.

Ground support provisions are provided for by two sets of two self sealing quick disconnects for the primary and secondary circuits. Each set of fittings provide for supply and return of the GSE coolant and are used for coolant fill and draining and ground cooling during equipment and system checkouts.

The secondary circuit coolant pump which only operates during flight if the primary system fails, circulates coolant through the emergency equipment - cold plates, water boiler and filter. The water boiler removes heat from the coolant by evaporation.

2.4 WATER MANAGEMENT

The water management section of the ECS stores the water for the metabolic needs of the crew, vehicle cooling and, for refilling the PLSS water tanks. The water management section consists of two water tanks in the ascent stage, one in the descent stage, water pressure regulators, check valves, shutoff valves and interconnecting tubing.

The water tanks are pressurized prior to earth launch to maintain the required pumping pressure in the water tanks. The water tank in the descent stage supplies a major portion of the water required up to the time of lunar launch. After lunar launch, water is obtained

from the two smaller tanks in the ascent stage. In addition to water from the tanks, water from the atmosphere revitalization section water separators is used in the water management section. The self-sealing PLSS water disconnect permits filling the PLSS water tanks and delivering of metabolic water for drinking and food preparation.

2.5 COLD PLATE

A cold plate is thermally affixed to each piece of electronic equipment requiring active temperature control. Coolant from the heat transport section passes through the cold plates and removes waste heat from the electronic equipment. There are two basic types of cold plates - structural and non-structural. Structural cold plates provide mounting support for the electronics as well as being a heat sink. Non-structural cold plates provide only a heat sink and are installed between the electronics and its supporting structure. Cold plates which serve electronics required for abort contain two separate coolant flow passages - one for primary loop coolant, the other for secondary coolant. Most of the other cold plates contain only a single flow passage for primary loop coolant.

3. MISSION-RELATED DESIGN CRITERIA

The spacecraft design ground rules and interface criteria which are applicable to the LEM ECS are presented in this section. Those identified by an asterisk differ from the requirements specified in the LEM Statement of Work (Reference 1) or authorized revisions and are discussed in Section 4.2.

3.1 APPLICABLE SPACECRAFT DESIGN GROUND RULES

3.1.1 Mission Duration

LEM systems shall be capable of meeting their nominal design performance level for a forty-eight hour mission following separation in lunar orbit. In addition, certain functions will be required during the period from earth pre-launch to separation in lunar orbit.

3.1.2 Surface Thermal Extremes

The LEM systems shall be designed to accommodate lunar surface day or night extremes on the near earth side of the moon.

3.1.3 Space Suits

The astronauts will be in their space suits during all lunar operations.

*3.1.4 PLSS

Extravehicular life support equipment and rechargeable consumables will provide the capability for a total of 28 manhours of separation from LEM systems, of which 24 manhours are for lunar surface operations. The back pack shall be rechargeable inside LEM.

3.1.5 Attitude Constraints

No attitude constraints shall be imposed on the LEM due to thermal considerations.

3.1.6 Orbital Contingency

The LEM ascent stage shall be designed to provide for a 9 hour orbital contingency in addition to the normal ascent requirements.

3.1.7 Crew Safety

Whenever possible, a system shall be designed so that the failure of any single element will not cause the loss of a crew member.

3.1.8 Surface Rescue

The LEM shall be designed to permit one crewman to assist the other on the lunar surface.

3.1.9 Alternate Exploration

During normal operations, only one LEM crew member at a time is permitted on the lunar surface and the other crew member shall remain awake inside the LEM.

3.2 INTERFACE CRITERIA

3.2.1 PLSS Charges

The initial complete charges for both PLSS units will be accomplished prior to LEM operations,

3.2.2 Oxygen Supply

CM ECS will provide and maintain pressurization of the interlock and LEM cabin for all manned operations prior to LEM separation. It shall also have the capability to pressurize the interlock and provide LEM metabolic and leak rate after final docking is accomplished.

*3.2.3 Use of CM Water

A portion of the water required for consumption, cooling and other needs may be obtained from the CM water reserves prior to LEM separation.

3.2.4 Pre-Launch Heat Rejection

Freon shall be supplied to the LEM by GSE, to satisfy all heat rejection requirements from LEM closeout to earth launch.

4. LEM ENVIRONMENTAL CONTROL SUBSYSTEM REQUIREMENTS

4.1 FUNCTIONAL REQUIREMENTS

The functional requirements of the LEM ECS are listed in this section. The ECS mission-related performance requirements are defined and related to the appropriate functional requirements. Many of these performance requirements result either from the criteria of Section 3.0 or the requirements imposed on the ECS by the other LEM subsystems. Those identified by an "asterisk" differ from the LEM Statement of Work (Reference 1) or authorized revisions, and are discussed in Section 4.2.

4.1.1 Oxygen Supply and Cabin Pressure Control

The ECS shall provide both the oxygen and the performance capability for maintaining the normal and emergency pressurization levels in the cabin and the space suit. The associated performance requirements are:

- During normal operation (2 crewmen in LEM) the LEM cabin will be pressurized to 5 ± 0.2 psi and the crew will wear unpressurized space suits.
- *● The ECS shall be designed to provide nine cabin repressurizations.
- *● Provisions shall be made for a cabin leak rate of 0.2 lb./hr. plus reserve oxygen supply equivalent to an additional leak rate of 0.2 lb./hr.
- The ECS must be capable of maintaining a cabin pressure of at least 3.5 psia for two minutes following puncture of the pressure shell by an equivalent 1/2 inch diameter hole and with the cabin initially at 5 psia.
- In the case of cabin decompression, the system shall provide conditioned O_2 atmosphere at a minimum pressure of 3.7 psia to the space suits.
- *● Under normal circumstances it is sufficient to be able to depressurize LEM within 5 minutes and to repressurize to a 3.7 psia level within one minute.
- *● For emergencies a decompression time of 3 minutes and a recompression time to a safe level (greater than 3 psia) in one minute is required.

4.1.2 Atmosphere Revitalization

The ECS must provide and condition the oxygen to cool and ventilate the space suits worn by the crew, and control the recirculation and temperature of the cabin gas. Proper conditioning of the oxygen supply shall include the control of:

- temperature
- relative humidity
- carbon dioxide partial pressure
- odors and noxious gases
- particles
- circulation

4.1.3 Thermal Control

The ECS shall provide temperature control of the electronic equipment, cryogenic fluids, and oxygen circulated through the cabin and space suits. A mission-related performance requirement is that no component critical to completion of the mission shall be dependent on the cabin gas temperature for thermal control.

4.1.4 Water Management

The ECS shall store the water required for the metabolic needs of the crew, water evaporators, PLSS, and emergency coolant in the heat transport section.

4.1.5 PLSS Recharge

The ECS shall provide the PLSS water, oxygen, and lithium hydroxide recharge capability required of the LEM. The back packs shall be capable of recharge in the LEM with the cabin either pressurized or unpressurized. The recharge capability shall consist of:

- *● 20 manhours of PLSS oxygen recharge requiring 0.307 lbs/manhour.
- *● 20 manhours of PLSS water recharge requiring 2.27 lbs/manhour.
- 24 manhours of PLSS LIOH recharge. (6 LiOH cannisters)

4.2 DISCUSSION

4.2.1 Critical Design Mission

The critical design mission forms the building block for establishing the requirements for sizing and staging of expendables in that it represents a composite of the most stringent time-oriented requirements for each of the mission phases. The ECS Critical Design Mission timeline is presented in Table I. Two lunar stay models are shown in the table. Profile A contains a maximum lunar stay of about 43 hours with a late launch ascent. Profile B shows a lunar stay of approximately 35 hours coupled with a nine-hour orbital

contingency. Some of the features of this timeline are described in Reference 2. The notable exceptions are the 110-hour translunar coast, lunar stay model, and LEM ascent.

The basic requirements for ascent and descent stage tank sizing shall be:

- To provide sufficient expendables in the LEM descent plus ascent stages to fly whichever mission (Profile A or Profile B) that requires the most expendables.
- To provide ascent stage expendables for a nine-hour orbital contingency in addition to the normal ascent requirements. The ascent requirements shall include provision for the final 30 minutes of the lunar surface prelaunch checkout. This allows the flexibility of either having a maximum lunar stay mission (Profile A) or a shorter lunar stay mission coupled with the flexibility for a nine hour orbital contingency.

The provisions for a 110-hour translunar coast allows the capability for "flying" slower non-free return trajectories to reduce the ΔV requirements, and for reaching higher latitude lunar landing sites within a given service module propellant budget. The entire problem of the effect of non-free return translunar trajectories on the envelope of lunar landing sites that can be reached merits further investigation.

A lunar stay model corresponding to the 43-hour stay of Profile A is shown in Figure 2. (See Section 4.2.2) It should be noted that Profile A includes an 8-minute-late launch, resulting in an approximately 60-minute parking orbit coast during LEM ascent, in conjunction with a 43-hour lunar stay. A 45-hour lunar stay combined with a nominal on-time launch (154° intercept ascent trajectory) would be another possible combination but was deemed to be less critical for expendable sizing. As a result of the 8-minute-late launch, ascent trajectory terminal rendezvous occurs in line-of-sight of the earth. Profile B includes an ascent trajectory which is compatible with a 9-hour orbital contingency.

4.2.2 Lunar Stay Model

The lunar stay model (Figure 2) was constructed to provide a reasonable but critical design stay, for use in sizing of expendables. The construction of a lunar stay model is strongly dependent on the assumed relation between work and rest cycles, and whether both astronauts in the LEM are permitted to sleep at the same time. A detailed discussion of the variables involved is contained in Reference 3. For the critical design lunar stay model (Figure 2) it was assumed that only one astronaut sleeps at a time in the LEM which resulted in a total of 18 man-hours of nominal lunar exploration time.

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There is also considerable interest in a 35-hour lunar stay (Profile B). If one assumed that only one man slept at a time in the LEM during a 35 hour surface stay, the total allowable exploration time on the lunar surface would be limited to about 12 man-hours. However, allowing both crewman to sleep at the same time facilitates more surface exploration periods. The model illustrated in Figure 4 shows 18 man-hours of nominal lunar exploration time during a 35-hour stay. This indicates that the full performance flexibility provided by the LEM ECS can be utilized during a 35-hour stay. A stay model similar to that contained in Figure 4 has been adopted in the Design Reference Mission (Reference 2).

4.2.3 Tank Sizing and Staging of Expendables

The critical mission timeline containing Profile A (43-hour stay) was determined to require the greater quantities of ECS expendables. Therefore for the ECS, the critical design mission (Table I) timeline in the left column (Profile A) represents the expendable sizing mission, and the time profile on the right (Profile B) represents a so-called staging mission primarily for sizing the ascent stage tanks. The ascent expendable tanks are sized for the final 30 minutes of prelaunch checkout plus ascent including the 9-hour orbital contingency (Profile B). The total LEM expendable requirements minus the ascent stage expendable loading size the descent stage tanks.

The expendables required for a 9-hour orbital contingency exceed those required for a nominal ascent so the ascent stage design of redundant water tanks protects against a tank failure. It is recommended that, for the expendable sizing mission (43-hour stay), redundant expendables for ascent be provided for a less-than-normal electrical power ascent profile (Reference 4).

Redundancy in expendables would be provided for an ascent tank failure at the beginning of lunar prelaunch checkout. Consequently, there would only be a short period of time during the mission where abort on a less-than-nominal equipment utilization profile would be necessary. This is different from the case of fuel cell failures, where the same equipment utilization ground rules apply no matter where in the mission the failure occurs. A recommendation of the actual profile is made in the EPS Design Requirements (Reference 4).

To summarize, the sizing and staging criteria for ECS expendables should proceed as follows:

1. Calculate the expendable requirements for nominal performance levels for the critical design mission from earth preflight operations through the initial lunar prelaunch preparation time of 70 minutes, using Profile A and Figure 2.
2. For the final lunar prelaunch preparation period of 30 minutes and the subsequent ascent of Profile A, calculate the expendable requirements using a lower equipment utilization ascent power profile and double this result to provide redundancy.
3. The sum of the expendable requirements of the first and second steps, for a particular consumable, represent the total useable expendable requirements in the ascent plus descent stage tanks for that consumable.
4. Calculate the expendable requirements for the final prelaunch preparation, ascent and orbital contingency, of Profile B with normal power utilization. This establishes the useable expendable requirements for the ascent stage tanks.
5. The difference between the expendable requirements of step 3 and step 4 established the useable expendable requirements for the descent stage tanks.

A calculation following this procedure is shown in Table IV.

4.2.4 Spacecraft Interface Criteria

In arriving at the LEM ECS critical design requirements it was assumed that there were certain interface requirements pertinent to LEM design. They are listed in the interface criteria (Section 3.1).

Two completely charged PLSS units are transferred to the LEM prior to separation in lunar orbit. These were assumed to provide 8 man-hours of PLSS expendables. It is recognized that the present PLSS oxygen and water capacities allow about three man-hours of lunar exploration. Therefore, some inconsistency exists in assuming that 8 man-hours of capability is provided at LEM separation. However, if the PLSS did not allow four man-hours of exploration, then the entire lunar stay model would have to be re-examined with the possible result that the allowable exploration time per excursion would be reduced. The net effect would probably be to reduce the man-hours of consumables that the LEM must provide for PLSS recharge. Therefore, the present assumption is believed to be both reasonable and conservative.

Certain assumptions have been made as to the CSM requirements to maintain pressure in LEM. The CSM must provide all pressurizations of both the interlock and the LEM prior to LEM separation and following docking. When the CSM and LEM are mated with the hatches open, it is advisable to have only one system provide metabolic plus leak rates for the entire spacecraft. As shown in the timeline (Table I), the LEM ECS begins removing

metabolic loads and carbon dioxide for the two crewmen in the LEM shortly after the LEM is activated. The supply of oxygen from the LEM does not begin until 90 minutes later or 6 minutes prior to separation (Reference 2). This is graphically illustrated in Figure 3, where the entire LEM ECS expendable timeline is presented.

The possibility of transferring water from the CSM to the LEM is currently under investigation. Two possible methods of utilizing the CSM water are:

1. Continuous transfer and use of CSM water from transposition to LEM separation.
2. Refill LEM water tanks during lunar orbit coast.

The LEM project has conducted a brief study on using CSM water and has suggested continuous transfer as the most feasible means of utilizing CSM water in the LEM. This mode of operating would minimize any LEM and CSM system modifications. This method also has the advantage of being able to use non-potable water from the CSM with a minimum weight penalty. Continual usage of CSM water would require a hose connection after transposition. Since a crew member must crawl into the interlock to complete the hard dock and connect electrical umbilicals, the mating of additional disconnects could easily be accommodated. The increase in LEM ECS hardware weight (hose, check valve, disconnects), to accommodate the transfer of water was estimated to be one pound. Continuous usage of CSM water would limit the maximum amount of water which could be transferred to about 75 pounds (see Table III). This transfer of water could result in a reasonable saving in translunar injected weight but would have a small effect on LEM separated weight. The size of the LEM descent stage water tank could be reduced by the amount of water to be transferred. This effect has been ignored in calculating LEM tank sizes because of the tentative nature of the proposed transfer scheme. However, the ability to obtain water from the CSM is recognized as a means of accruing increased flexibility for the LEM.

4.2.5 PLSS Recharge Capability

The spacecraft design ground rule (3.1.4) that must be satisfied is that a total capability of 28 man-hours of separation from LEM be provided, of which 24 man-hours are for lunar surface operations. The 24 man-hours for surface exploration is divided into 6 three hour excursions with 1-hour reserve provision for each excursion, making a total of 18 man-hours nominal plus six man-hours for reserve. However, part, or all, of this six man-hour margin could be used for further lunar surface exploration. Four man-hours of additional recharge capability is stored in the ascent stage to provide an ascent contingency

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allowance. This contingency allowance together with the six man-hours of margin mentioned previously is considered to be more than adequate to handle any eventuality.

When the ground rule (3.1.4) is combined with the interface criteria (3.2.1), the ECS functional requirement (4.1.5) results. Eight man-hours of PLSS charge is assumed to be transferred to the LEM as discussed in Section 4.2.4. The requirement for 20 man-hours of both oxygen and water recharge capability is straight-forward. However, each PLSS lithium hydroxide cartridge has four man-hours capacity and three man-hours is consumed on a nominal excursion. Consequently, one man-hour per excursion cannot be nominally used and 24 man-hours of lithium hydroxide recharge capability must be provided to be consistent with the other PLSS requirements. Although only two hours of PLSS capacity/man is believed necessary to handle an ascent contingency situation, only one or four man-hours per useable cartridge can be guaranteed. Therefore two fully charged cartridges are provided for lunar launch. However, a partially spent lithium hydroxide PLSS cartridge could be used to advantage in the ECS by-pass loop.

In order to reduce the turn around time for lunar egress following two consecutive lunar excursions, and to provide complete flexibility for ascent and for assisting an astronaut on the lunar surface, it is recommended that a spare PLSS battery be carried on board the LEM.

4.2.6 Cabin Repressurizations and Leak Rate

The need to provide for nine cabin repressurizations result from the requirement for a 43-hour lunar stay or an efficient 35-hour stay (Figure 4). The maximum possible time out on the lunar surface for a 43-hour stay within the operational constraints is approximately 20 hours (Reference 3). Therefore, allowing for a nominal 18 hours of lunar exploration (Figure 2) seems reasonable. The plausible requirement that the cabin be pressurized when one astronaut is on the lunar surface in conjunction with six excursions, (each of three hours duration) results in a design requirement to provide (size) for nine cabin repressurizations. It is desirable to provide a comfortable environment for the astronaut in LEM especially since he will have, in most cases, just spent three hours in a hard suit. It is recommended that the tank sizing and operational requirements be that six of the nine repressurizations be to 3.7 ± 0.2 psia. with three repressurizations to 5 ± 0.2 psia.

The recommendation that six of the nine cabin repressurizations be to 3.7 ± 0.2 psia is based primarily on four points:

1. It is physiologically sound.
2. It does not affect crew safety.
3. Sizing for nine repressurizations to 5 psi in conjunction with an allowable cabin leak rate of 0.4 lb/hr results in a large weight penalty.
4. Repressurization to 3.7 psia can be accommodated within the present ECS design without major modifications.

It is recommended that six repressurizations to 3.7 psia be used when one astronaut is on the lunar surface (see Figure 2). There seems to be little question that a 3.7 psia pure oxygen environment is as habitable as a 5 psi environment from the physiological point of view. The astronaut in the LEM would be on active duty while the cabin is at 3.7 psi. Consequently, the possibility that cabin decompression, due to a sudden leak, would endanger the astronaut's life is extremely remote.

The amount of oxygen required to provide nine cabin repressurizations represents a significant weight penalty. Sizing six of the cabin cycles for 3.9 psia rather than 5.2 psia, results in approximately a 10 lb. saving in oxygen. This assumes that a pressurization to 5.2 psia requires 6.9 lb. of oxygen. There is considerable redundancy and conservatism built into the oxygen sizing criteria and it is reasonable to assume that on the majority of missions, the capability will exist to provide nine complete repressurizations to 5 psia. One pertinent example of conservatism is allowable cabin leak rate. The design requirements for the cabin pressure shell specifies an allowable leak rate of 0.2 lb/hr. However, due to the uncertainty in being able to predict what leak rates may actually be attainable and a change in cabin fabrication methods, it has been recommended that the ECS size its oxygen supply for a total equivalent leak rate of 0.4 lb/hr. at 5 psia. If the cabin leak rate did not exceed 0.2 lb/hr, then there would be sufficient oxygen available for nine complete cabin repressurizations to 5 psi. Therefore, in a sense, repressurization to 3.7 psia and sizing for an allowable maximum leak rate of 0.4 lb/hr go hand in hand.

The present ECS hardware design would be able to accommodate a mode of repressurization to $3.7 + 0.2$ psia without major modifications. Of course, a more detailed study of the implications to the ECS would have to be performed, if this recommended procedure were adopted.

4.2.7 Evaluation of Expendable Requirements

In this section, the ECS expendable requirements for the critical design mission are calculated. The critical mission timeline (Table I) in conjunction with the 43-hour lunar stay profile (Figure 2) established both the time profile and sequence of events for the calculations. Expendable calculations were performed for water, oxygen, and lithium hydroxide. The water tanks and the lithium hydroxide cartridges are stored in the ECS and are evaluated here. The oxygen tanks, and indeed the bulk of the oxygen expendable requirements, are part of the EPS. Therefore, the ECS oxygen requirements are discussed here, but the actual tank sizing and staging criteria are evaluated in the EPS Critical Design Requirements. It should be noted that the water sizing requirements were based on the 121 kilowatt hour electrical energy profile which is the design point for EPS expendable sizing.

A complete cumulative expendable profile for the ECS is shown in Table III. The table includes metabolic and cabin leak rates for oxygen by mission phase. The expendable profiles for water, oxygen, and lithium hydroxide are plotted in Figures 5, 6, and 7 respectively. The cumulative expendable totals in Table III do not actually size the tanks, since the mission in the table is a so-called critical design nominal mission and therefore, does not include orbital contingency or ascent redundancy considerations. The LEM lithium hydroxide cartridges, however, are not staged and are backed up by the PLSS cartridges. Therefore, the cumulative lithium hydroxide total of 79.8 man-hours can be considered a critical design value. The current value for sizing is 82 man-hours which is in excellent agreement with the calculated value.

The water sizing requirements were calculated using the data from Table III and is summarized in Table IV. The procedure used is the "recipe" for tank sizing outlined in Section 4.2.3. An "abort" ascent power profile, for calculating expendable redundancy, is not currently available. Preliminary studies have indicated that the "abort" profile would require about 70% of the electrical energy of a nominal ascent. Therefore, it was assumed that the "abort" profile would utilize 75% of the water requirements for a nominal ascent. The total water requirements, as shown in Table IV, is 392.5 lb. of useable water, 66.6 lb. of which should be stored in two redundant ascent stage tanks and the remaining 325.9 lb. in a single descent water tank. The current LEM ECS water tank design contains 306.3 lb. of useable water in the descent stage and 76.3 lb. in the ascent stage for a total useable quantity of 382.6 lb. Therefore, the current ECS design is sized for approximately 10 lbs.

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less than this calculation indicated, but with somewhat larger ascent tanks. This is considered to be a reasonable agreement. The 10 lb. of water could easily be made up by varying the mission slightly, for instance, by flying a translunar coast not greater than 95 hours. In addition, the possibility of transferring water from the CSM to the LEM (see Section 4.2.4) would make more than 10 lbs. of water available to the LEM. As a matter of fact, if transfer of water from the CSM became a reality, the size of the current descent stage water tank could even be reduced.

The discrepancy in ascent water tank sizing is due to assuming different mission profiles for ascent. In this study, a nominal intercept ascent trajectory was coupled with the nine-hour orbital contingency, and only the final 30 minutes of prelaunch checkout was included in the ascent water requirements. The current (LEM Project) design philosophy makes slightly more conservative assumptions (see Table II).

The cumulative oxygen totals for the nominal critical design mission are shown in Table III and plotted in Figure 6. As mentioned earlier the actual oxygen sizing requirements must be evaluated under the EPS requirements. As far as the ECS portion of the requirements are concerned, the oxygen quantities calculated here add up to about 10 lb. more oxygen than the current design value. This is due mainly to the recommended increase in cabin repressurizations from six to nine.

4.2.8 ECS Requirements Summary

The previous sections described in some detail the requirements related to sizing and staging of expendables. A summary sheet of all the ECS functional requirements, including the parameters which are not expendable oriented, is presented in Table II. The table includes the subsystem function, the mission event or profile which sizes the parameter or value, and the current design value where applicable. Some of the expendable requirements are repeated here for completeness.

The ascent and descent stage ECS SOX requirements are derived from the critical design mission. The final sizing criteria for the ascent and descent SOX tanks are evaluated in the EPS design requirements report, Reference 4, where the ECS oxygen requirements are used as an input. The current capability for PLSS oxygen and water recharge was originally believed to be for 24 man-hours from the descent SOX and 4 man-hours from the ascent SOX. This capability is possibly only worth 3/4 of these PLSS man hours because of higher metabolic estimates.

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The GOX bottle requires 7.46 lb. above 150 psia for backup of the ascent SOX supply. GOX storage capacity at 850 psia and 160°F is 9.3 lb. of which 7.1 lb. is available above 150 psia. The actual sizing of the GOX tank is discussed in the EPS design requirements report, Reference 4.

The present ECS design does not include a nominal cabin pressure mode of 3.7 PSIA.

Rapid cabin repressurization, within one minute, is considered a requirement for both nominal and contingency situations. The requirements for nominal cabin dump in five minutes and emergency dump in three minutes are somewhat arbitrary. These requirements allow maximum crew comfort, minimum interference with lunar surface operations and some protection against space suit assembly contingencies. The LEM has two cabin dump valves; one located in each of the two LEM hatches. If one valve is opened, the cabin will dump in approximately three minutes. This is the normal mode. In an emergency, both cabin dump valves can be opened and the cabin can be dumped in about 1.5 minutes.

Most of the other items in Table II are self-explanatory. The requirements for equipment thermal control by the back-up glycol loop are currently being re-evaluated by the LEM project. In the event that complete redundancy is impractical, it is recommended that the equipment utilization philosophy for the back-up loop be consistent with the multiple fuel cell failure survival requirements for the EPS.

5. CONCLUSIONS AND RECOMMENDATIONS

The two major purposes of this document were to define the ECS mission-related critical design criteria, and calculate the expendable capacities required to satisfy these criteria. It was concluded that the LEM should be designed to provide the option of the following:

1. Maximum possible stay on the lunar surface within the constraint of a 48-hour separated LEM.
2. A shorter lunar surface stay (of approximately 35 hours) plus provisions for a nine-hour orbital contingency in addition to the normal ascent requirements.

An evaluation of the expendable requirements to satisfy these options indicate that the current LEM Project useable expendable quantities are adequate. The small discrepancy in expendable weights, (see Section 4.2.8) was mostly due to differences in the assumptions that were made, many of which were somewhat arbitrary in nature.

The maximum possible lunar surface stay, for a 48-hour separated LEM is 45 hours. However, the recommended critical design mission contains a 43-hour lunar stay coupled with an eight minute late launch because this imposes more stringent expendable sizing requirements. The full 45-hour lunar stay does not permit the late launch flexibility since that combination would exceed the 48-hour LEM mission time.

The LEM ascent stage is designed to provide for a nine hour orbital contingency in addition to the normal ascent requirements. Ascent stage expendables would be used up on the lunar surface for stay times longer than about 35 hours. Of course, a longer than 35-hour lunar stay would be planned only if the requirement to provide for a nine-hour orbital contingency were relaxed.

It is recommended that PLSS expendables be provided for a total of 28 man-hours of separation from LEM systems. Up to 24 man-hours of this total could be utilized for lunar surface exploration with four man-hours allotted for contingencies during LEM ascent. The critical design mission shows 18 man-hours of nominal lunar surface exploration time. The additional six man-hours of capability could be used for further surface explorations. Two

extra PLSS lithium hydroxide cartridges are necessary in order to meet the 28-man-hour requirement.

It is desirable to have the capability for repressurizing the LEM cabin when one astronaut is on the lunar surface. In order to be compatible with extended lunar stay times of up to 45 hours and the available extravehicular exploration capability, it is recommended that provision be made in the LEM for nine cabin repressurizations. In evaluating the expendable sizing requirements, six of the nine repressurizations were to a 3.7 ± 0.2 psia level. The oxygen supply stored on board the LEM is sufficient to provide nine such repressurizations (see Reference 4). It is also recommended that an extra PLSS battery be carried on board the LEM to provide maximum flexibility for lunar surface exploration.

A requirement in evaluating expendable tank sizing was that ascent on a nominal trajectory could be accomplished if an ascent expendable (hydrogen, oxygen, or water) tank failed at any point in the mission. The design point that was chosen was failure of an ascent tank during the final prelaunch checkout combined with an eight-minute-late launch ascent trajectory. For this case it was recommended that the ascent be on a lower equipment utilization electrical power profile. This mode of failure has different implications on equipment utilization requirements than the case of fuel cell failures and was therefore evaluated separately.

The following subjects merit further study and evaluation:

- The possible transfer of water from the CSM to the LEM.
- The feasibility of maintaining 3.7 psia cabin pressure as a normal operating mode.
- Ascent on a less-than-normal equipment utilization power profile for contingencies other than fuel cell failures.

It should be noted that transfer of water from the CSM to the LEM could reduce the earth launch weight, but would essentially not affect the LEM separation weight.

6. REFERENCES

1. Lunar Excursion Module Project Apollo, Exhibit B Technical Approach, Contract No. NAS-9-1100, 20 December 1962, ~~CONFIDENTIAL~~
2. Design Reference Mission, Apollo Mission Planning Task Force, GAEC Report No. LED-540-12, 30 October 1964 (three volumes) ~~CONFIDENTIAL~~
3. W. Baker and D. Treffeisen, Lunar Surface Stay Constraints and Mission Designs, Apollo Mission Planning Task Force, GAEC Report No. LED-540-11, 28 August 1964.
4. E. M. Finkelman, H. A. Bell and C. Keenan, Mission Related Design Requirements for the LEM Electrical Power Subsystem, Apollo Mission Planning Task Force, GAEC Report No. LED-540-22, 9 November 1964, ~~CONFIDENTIAL~~
5. LEM Environmental Control Systems Meeting No. 4, Abstract of Proceedings, NASA Manned Spacecraft Center, 15 August 1963.

TABLE I
ESC CRITICAL DESIGN MISSION

Phase		Phase Time			
		Min.	Hrs.		
1.0	Preflight	900	15.0		
2.0	Earth Ascent	11.8	0.20		
3.0	Earth Parking Orbit (3 Orbits)	270	4.5		
4.0	Translunar Injection	5.2	0.09		
5.0	Initial Translunar Coast Thru S IV-B Jettison	60	1.0		
6.0	S IV-B Jettison to Lunar Orbit Insertion	6540	109.0		
7.0	Lunar Orbit Insertion	5.4	0.09		
8.0	Lunar Orbit Coast to LEM Separation				
8.1	Lunar Orbit Coast	110	1.8		
8.2	Preparation for LEM Separation				
	Initial (CSM Supplies O ₂)	90	1.5		
	Final (LEM Supplies O ₂)	6	0.1		
9.0	CSM Solo Operations				
10.0	LEM Separation and Descent				
10.1	Separation and Preparation for Descent	30	0.5		
10.2	Transfer Orbit Insertion	0.6	0.01		
10.3	Coast to Powered Descent Initiation	58	1.0		
10.4	Powered Descent to Hover	8.4	0.14		
10.5	Hover to Touchdown	2	0.03		
11.0	LEM Lunar Stay	Profile A		Profile B	
		Min.	Hrs.	Min.	Hrs.
11.1	Post Landing Checkout	75	1.25	75	1.25
11.2	Lunar Exploration	2401	40.02	1909	31.82
11.3	Prelaunch Preparation				
	Initial (Descent Expendables)	70	1.17	70	1.17
	Final (Ascent Expendables)	30	0.50	30	0.50
	Hold (Late Launch)	8	0.13		
12.0	LEM Ascent				
12.1	Powered Ascent	7.5	0.12	7.5	0.12
	Orbital Contingency			540	9.0
12.2	Coast to Terminal Rendezvous	107	1.78	65	1.08
12.3	Terminal Rendezvous	7.5	0.12	7.5	0.12
12.4	Docking				
	Initial (LEM Supplies O ₂)	17	0.28	17	0.28
	Final (CSM Supplies O ₂)	25	0.42	25	0.42

TABLE II

LEM ENVIRONMENTAL CONTROL SUBSYSTEM REQUIREMENT SUMMARY

Subsystem Function	Parameters Which Describe Function	Mission Events or Profile Which Sizes Parameter and Value	Current Design Value
Supply O ₂ and maintain suit and cabin pressure	ECS Descent SOX Quantity	<p><u>NOMINAL:</u> 79.5 lb for 43 hour lunar stay (see Figure 2); 9 cabin repressurizations - 6 to 3.9 psia and 3 to 5.2 psia; 18 manhours of PLSS recharge; initial prelaunch checkout (70 min.)</p> <p><u>CONTINGENCY:</u> Sizing based on total ascent plus descent stage requirements minus ascent stage sizing (see Section 4.2.3).</p>	154.1 lb useable for ECS and EPS.
	ECS Ascent SOX Quantity	<p><u>NOMINAL:</u> 1.7 lb, final lunar prelaunch checkout (30 min.) plus ascent requirements.</p> <p><u>CONTINGENCY:</u> 6.9 lb, final lunar prelaunch checkout (30 min.) plus normal ascent plus 9 hour orbital contingency plus 2 manhours of PLSS recharge.</p>	Originally sized for 35 hour lunar stay; 6 cabin repressurizations to 5.2 psia; 18 manhours of PLSS recharge.
	GOX Quantity (Ascent)	<p><u>NOMINAL:</u> 6.9 lb for one cabin repressurization to 5.2 PSIA.</p> <p><u>CONTINGENCY:</u> 7.46 lb above 150 psia. Backup of ascent SOX supply - All O₂ requirements for final checkout (30 min) plus ascent. (Calculated in Reference 4)</p>	21.66 lb useable for ECS and EPS. 100 min. prelaunch checkout (EPS); normal ascent; 9 hour orbital contingency; 3 manhours of PLSS recharge.
	Cabin Pressure	<p><u>NOMINAL:</u> 5± 0.2 psia with 2 men in vehicle, 3.7^{+0.2}_{-0.0} with 1 man exploring.</p> <p><u>CONTINGENCY:</u> Loss of cabin pressure due to puncture, switch to closed suit loop operation.</p>	9.3 lb useable, 7.1 lb above 150 psia. Backup for ascent SOX supply, also normal ECS ascent and full 100 min. pre-launch C/O.
	Suit Pressure	<p><u>NOMINAL:</u> 5± 0.2 psia with 2 men in vehicle, 3.7^{+0.2}_{-0.0} with 1 man exploring.</p> <p><u>CONTINGENCY:</u> 3.7^{+0.2}_{-0.0} psia (closed suit loop operation) if cabin is punctured.</p>	Same except no 3.7 psia mode.
			SAME

TABLE II - Continued

Subsystem Function	Parameters Which Describe Function	Mission Events or Profile Which Sizes Parameter and Value	Current Design Value
Atmosphere Revitalization	O ₂ Rate	<p><u>NOMINAL:</u> Cabin repressurization to 3.7 psia within 1 minute. Cabin dump in 5 minutes</p> <p><u>CONTINGENCY:</u> Cabin repressurization to 3.7 psia within 1 minute. Cabin dump in 3 minutes. Suit purge at 13.6 lb/hr.</p>	SAME if repressurized by GOX
	Suit Circuit Circulation Rate	<p><u>NOMINAL:</u> Extremes of metabolic output and CO₂ dilution. 12 cfm at 3.5 psia and 70° F as per Reference 5.</p> <p><u>CONTINGENCY:</u> None</p>	SAME
	CO ₂ Removal	<p><u>NOMINAL:</u> Integrated metabolic rates by mission phase (see Table III). Maximum allowable CO₂ partial pressure is 7.6 mm of Hg. Requires 80 manhours of CO₂ removal capability.</p> <p><u>CONTINGENCY:</u> None</p>	82 manhours of CO ₂ removal capability plus backpack canisters.
	Noxious Gases	<p><u>NOMINAL:</u> Metabolic odors.</p> <p><u>CONTINGENCY:</u> None</p>	1.32 lb. charcoal.
	Particles	<p><u>NOMINAL:</u> LiOH particles</p> <p><u>CONTINGENCY:</u> None</p>	Filtration for maximum particle dia. of 25 microns.
	Cabin Temperature	<p><u>NOMINAL:</u> Cabin temperature of 75° ±5° for high noon and night on lunar surface.</p> <p><u>CONTINGENCY:</u> Loss of primary glycol loop - no temperature control of equipment.</p>	SAME
	Cabin Gas Circulation Rate	<p><u>NOMINAL:</u> Circulation rate of 10 lb/min. at 5 psia or 7.8 lb/min. at 3.9 psia for worst heat load of high noon on lunar surface.</p> <p><u>CONTINGENCY:</u> None</p>	SAME
	Suit Temperature	<p><u>NOMINAL:</u> Extremes of metabolic output. 1428 BTU/hr total steady state.</p> <p><u>CONTINGENCY:</u> None</p>	SAME

TABLE II - Continued

Subsystem Function	Parameters Which Describe Function	Mission Events or Profile Which Sizes Parameter and Value	Current Design Value
Atmosphere Revitalization (Cont)	Relative Humidity	<u>NOMINAL:</u> 40-70% in cabin. <u>CONTINGENCY:</u> None	SAME
Water Management	Descent Water Quantity	<u>NOMINAL:</u> 350 lb useable (see Table IV). Includes 43 hr stay (Fig 2), 18 man-hours of PLSS recharge, 70 min. of prelaunch checkout. <u>CONTINGENCY:</u> 325.9 lb useable (Table IV). Based on total required both stages minus ascent sizing (see Section 4.2.3).	306.3 lb useable.
	Ascent Water Quantity	<u>NOMINAL:</u> 25.4 lb useable (see Table IV). Includes final prelaunch checkout of 30 min and ascent requirements. <u>CONTINGENCY:</u> 66.6 lb useable (Table IV). Final lunar prelaunch checkout of 30 min. plus normal ascent plus 9 hour orbital contingency plus 2 manhours of PLSS recharge.	76.3 lb useable stored in two tanks.
Thermal Control of Equipment	Heat Transfer Rate to Cryogenics	<u>NOMINAL:</u> 2500 BTU/hr to H ₂ during hover-to-touchdown, 319 BTU/hr to O ₂ during post landing checkout. <u>CONTINGENCY:</u> None for H ₂ . 600 BTU/hr to O ₂ when filling GOX during powered ascent.	2500 BTU/hr - H ₂ 600 BTU/hr - O ₂
	Heat Transfer Rate to Glycol Loop	<u>NOMINAL:</u> 5054 BTU/hr during rendezvous and docking. <u>CONTINGENCY:</u> Backup glycol loop sized for abort profile load.	SAME except backup loop load being evaluated.

TABLE III
ECS CRITICAL DESIGN MISSION

Phase	Duration Hrs.	Time From Launch-Hr	Water #/Phase	Water From Launch-#	Men In LEM	Meta- bolic O ₂ #/man-hr.	Cabin Leak #/Hr.	PLSS O ₂ Fill #/Hr	O ₂ #/Phase	O ₂ From Launch #	LiOH Man-hr./Phase	LiOH Man-hr. From Launch
1.0 Preflight	-15	-15	0	0	-	-	-	-			-	-
2.0 Earth Ascent	0.2	0.2	0.140	0.14	-	-	-	-			-	-
3.0 Earth Parking Orbit	4.5	4.7	2.890	3.03	-	-	-	-			-	-
4.0 Translunar Injection	0.1	4.8	0.064	3.09	-	-	-	-			-	-
5.0 Initial Translunar Coast Thru S-IVB Jettison	1.0	5.8	0.642	3.73	-	-	-	-			-	-
6.0 SIV-B Jettison to Lunar Orbit Insertion	109	114.8	69.978	73.71	-	-	-	-			-	-
7.0 Lunar Orbit Insertion	0.1	114.9	0.064	73.77	-	-	-	-			-	-
8.0 Lunar Orbit Coast to LEM Separation												
8.1 Lunar Orbit Coast	1.8	116.7	1.155	74.93	-	-	-	-	1.0		-	-
8.2 Preparation for LEM Separation:												
Initial Checkout (CSM Supplies O ₂)	1.5	118.2	10.830	85.76	2	.082	0.4	-			2.90	2.90
Final Checkout (LEM Supplies O ₂)	0.1	118.3	0.722	86.48	2	.082	0.4	-	.05	1.05	.19	3.09
10.0 LEM Separation & Descent												
10.1 Separation & Preparation for Descent	0.5	118.8	4.275	90.76	2	.113	0.4	-	.31	1.36	1.33	4.42
10.2 Transfer Orbit Insertion	0.01	118.81	0.135	90.89	2	.113	0.4	-	.01	1.37	.044	4.46
10.3 Coast to Powered Descent Initiation	0.97	119.78	7.755	98.65	2	.085	0.4	-	.56	1.93	1.948	6.41
10.4 Powered Descent to Hover:												
Initial Powered Descent	0.1	119.88	0.850	99.50	2	.124	0.4	-	.06	2.00	.292	6.70
Final Powered Descent	0.04	119.92	0.351	99.85	2	.124	0.4	-	.02	2.02	.115	6.82
10.5 Hover to Touchdown	0.033	119.95	0.302	100.15	2	.124	0.4	-	.02	2.04	.096	6.91
11.0 LEM Lunar Stay:												
11.1 Post Landing Checkout	1.25	121.20	9.150	109.30	2	.117	0.4	-	.79	2.84	3.44	10.35
11.2 Lunar Exploration:												
Cabin Decompression to Refill	0.25	121.45	1.009	110.31	2	.085	0	-	.04	2.88 - 8.06	.5	10.85
#1 Explore	3.0	124.45	14.280	124.59	1	.082	0.312	-	1.18	9.24	2.895	13.75
Transfer & Charge PLSS to Cabin Refill	0.25	124.70	7.809	132.40	2	.091	0	3.68	.96	10.21 - 15.39	.53	14.28
#2 Explore	2.75	127.45	13.090	145.49	1	.082	0.312	-	1.08	16.47	2.65	16.93
Cabin Decompression to Refill	0.25	127.70	1.009	146.50	1	.085	0	-	.02	16.49 - 23.39	.25	17.18
Recharge PLSS	0.25	127.95	8.015	154.51	2	.091	0.4	3.68	1.06	24.46	.53	17.71
Coordination	0.75	128.70	3.645	158.16	2	.085	0.4	-	.42	24.89	1.5	19.21
#1 Sleep	4.0	132.70	19.440	177.60	2	.081	0.4	-	2.24	27.13	7.64	26.85
Coordination	0.5	133.20	2.430	180.03	2	.085	0.4	-	.28	27.42	1.0	27.85
#2 Sleep	4.0	137.20	19.440	199.47	2	.081	0.4	-	2.24	29.67	7.64	35.49
Coordination	0.5	137.70	2.430	201.90	2	.085	0.4	-	.28	29.95	1.0	36.49
Cabin Decompression to Refill	0.25	137.95	1.009	202.90	2	.085	0	-	.04	30.00 - 35.18	.5	36.99
#1 Explore	3.0	140.95	14.280	217.18	1	.082	0.312	-	1.18	36.36	2.895	39.88
Transfer & Charge PLSS to Cabin Refill	0.25	141.20	7.809	224.99	2	.091	0	3.68	.96	37.33 - 42.51	.53	40.41
#2 Explore	2.75	143.95	13.090	238.08	1	.082	0.312	-	1.08	43.59	2.65	43.06
Cabin Decompression to Refill	0.25	144.20	1.009	239.09	1	.085	0	-	.02	43.61 - 50.51	.25	43.31
Recharge PLSS	0.25	144.45	8.015	247.11	2	.091	0.4	3.68	1.06	51.58	.53	43.84
Coordination	0.75	145.20	3.645	250.75	2	.085	0.4	-	.42	52.00	1.50	45.34
#1 Sleep	4.0	149.20	19.440	270.19	2	.081	0.4	-	2.24	54.25	7.64	52.98
Coordination	0.5	149.70	2.430	272.62	2	.085	0.4	-	.28	54.54	1.0	53.98
#2 Sleep	4.0	153.70	19.440	292.06	2	.081	0.4	-	2.24	56.78	7.34	61.32
Coordination	0.5	154.20	2.430	294.49	2	.085	0.4	-	.28	57.07	1.0	62.32
Cabin Decompression to Refill	0.25	154.45	1.009	295.50	2	.085	0	-	.04	57.11 - 62.29	.5	62.82
#1 Explore	3.0	157.45	14.280	309.78	1	.082	0.312	-	1.18	63.48	2.895	65.72
Transfer & Charge PLSS to Cabin Refill	0.25	157.70	7.990	317.77	2	.091	0	3.68	.96	64.44 - 69.62	.53	66.25
#2 Explore	2.75	160.45	13.090	330.86	1	.082	0.312	-	1.08	70.70	2.65	68.90
Cabin Decompression to Refill	0.25	160.70	1.009	331.87	1	.085	0	-	.02	70.73 - 77.63	.25	69.15
Recharge PLSS	0.25	160.95	8.015	339.89	2	.091	0.4	3.68	1.06	78.68	.53	69.68
Coordination	0.25	161.20	1.215	341.10	2	.085	0.4	-	.14	78.83	.5	70.18
11.3 Prelaunch Checkout	1.66	162.86	12.671	353.77	2	.082	0.4	-	.93	79.77	3.21	73.39
HOLD (Late Launch)	0.133	162.99	0.646	354.42	2	.082	0.4	-	.06	79.83	.26	73.65
12.0 LEM Ascent												
12.1 Powered Ascent	0.125	163.12	1.060	355.48	2	.117	0.4	-	.08	79.92	.344	73.99
12.2 Coast to Terminal Rendezvous	1.78	164.90	14.660	370.14	2	.085	0.4	-	1.01	80.93	3.56	77.55
12.3 Terminal Rendezvous	0.125	165.02	1.09	371.23	2	.101	0.4	-	.07	81.00	.298	77.85
12.4 Docking:												
Initial (LEM Supplies O ₂)	0.3	165.32	2.619	373.85	2	.117	0.4	-	.19	81.19	.825	78.68
Final (CSM Supplies O ₂)	0.4	165.72	1.524	375.38	2	.117	0.4	-	-	-	1.1	79.78

NOTES: A. 1# O₂ Leak During Unmanned Phases.

B. LiOH Man-hours are based on Metabolic O₂, Consumption of .085#/man-hr.

C. O₂ for Cabin Recharge
6.9# at 5.2 psia
5.18# at 3.9 psia

D. Water provided for crew consumption is 1200 cc/
man/day (amount lost by urination).

TABLE IV
WATER SIZING

Total Water Required

Earth preflight thru initial prelaunch checkout (Table III) for critical design mission	350 lb.
Low equipment utilization (75%) ascent, final prelaunch checkout thru final docking, .75 (25.4) = 19 lb.	
Total ascent sizing for redundancy, 2 (19)	38
PLSS recharge for 2 man hours, ascent contingency	4.5
	<hr/>
T O T A L water, ascent plus descent	392.5 lb.

Ascent Stage Water Required

	Phase Duration Min.	
11.3 Final prelaunch checkout	30	3.8 lb.
12.1 Powered Ascent	7.5	1.1
Orbital Contingency		
A	30	4.0
B	420	27.9
C	90	11.4
12.2 Coast to Terminal Rendezvous	65	8.9
12.3 Terminal Rendezvous	7.5	0.9
12.4 Docking	42	4.1
PLSS recharge for 2 man hours		4.5
		<hr/>
T O T A L (in two tanks)		66.6 lb.

Descent Stage Water Required

Ascent plus descent	392.5 lb.
Ascent stage required in two tanks	66.6
	<hr/>
D I F F E R E N C E	325.9 lb.

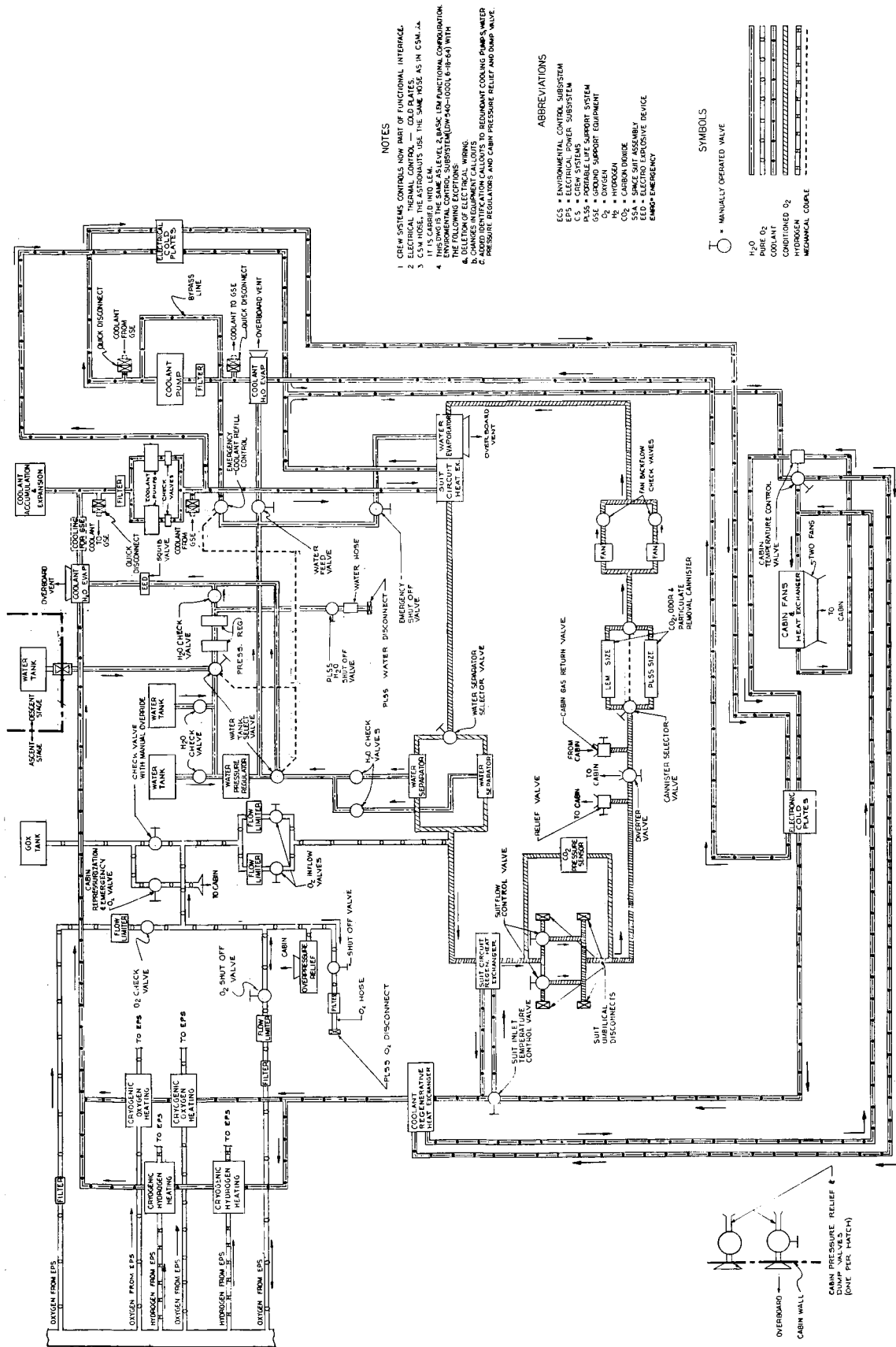


Figure 1 - Environmental Control Subsystem Functional Diagram



Figure 2 - Lunar Stay Profile, 43 Hours

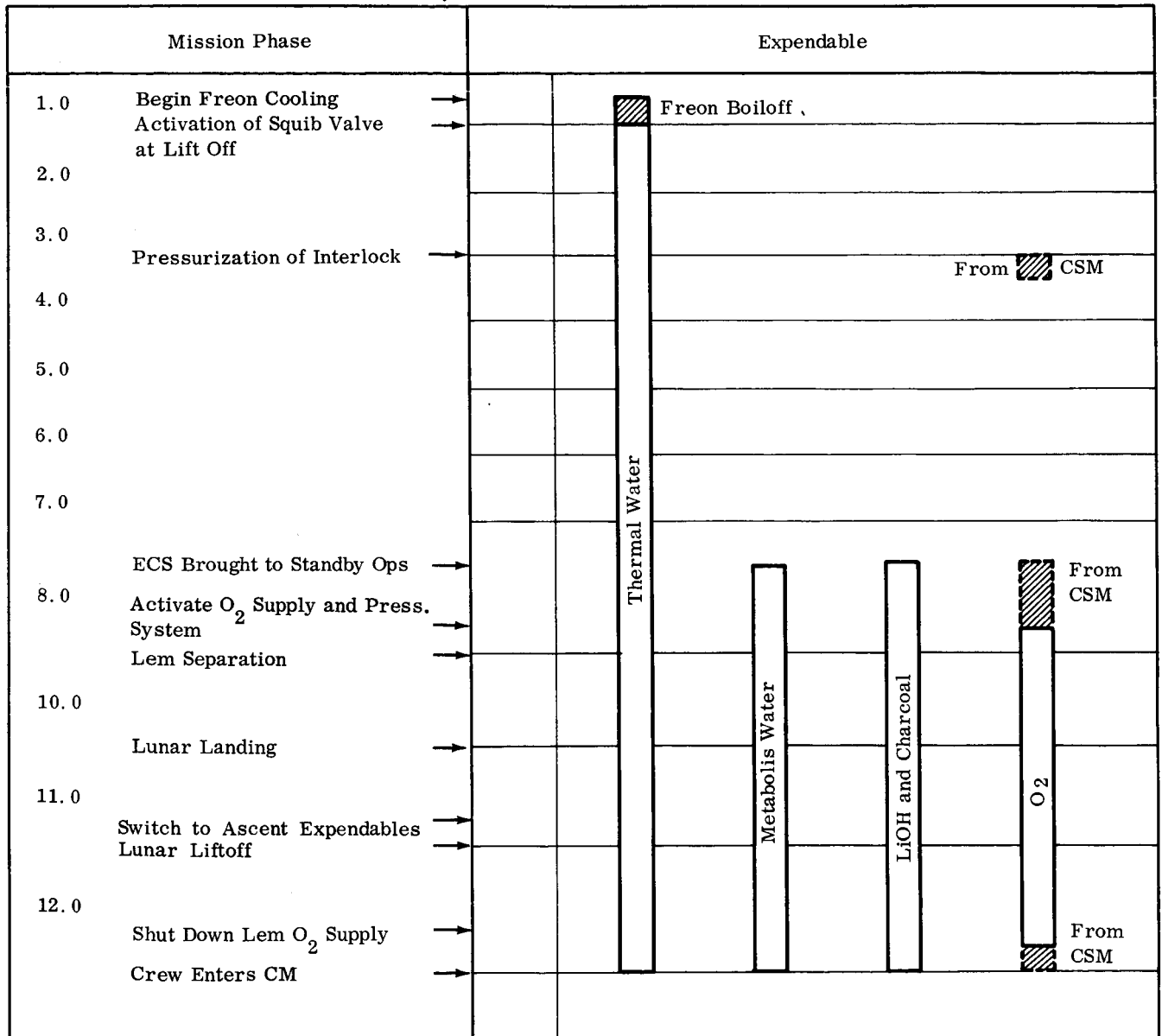


Figure 3 - ECS Expendables Timeline

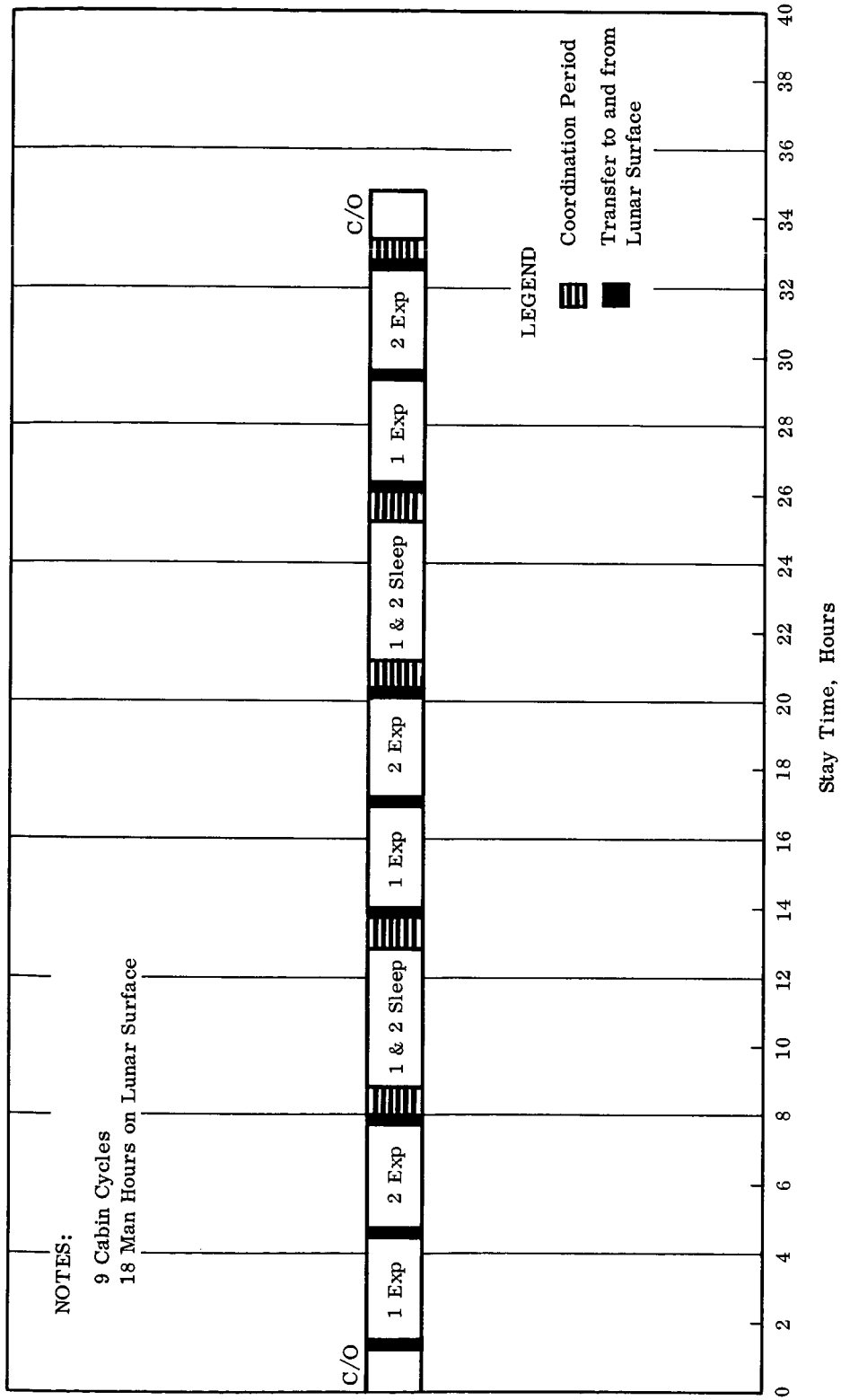


Figure 4 - Lunar Stay Profile, 35 Hours

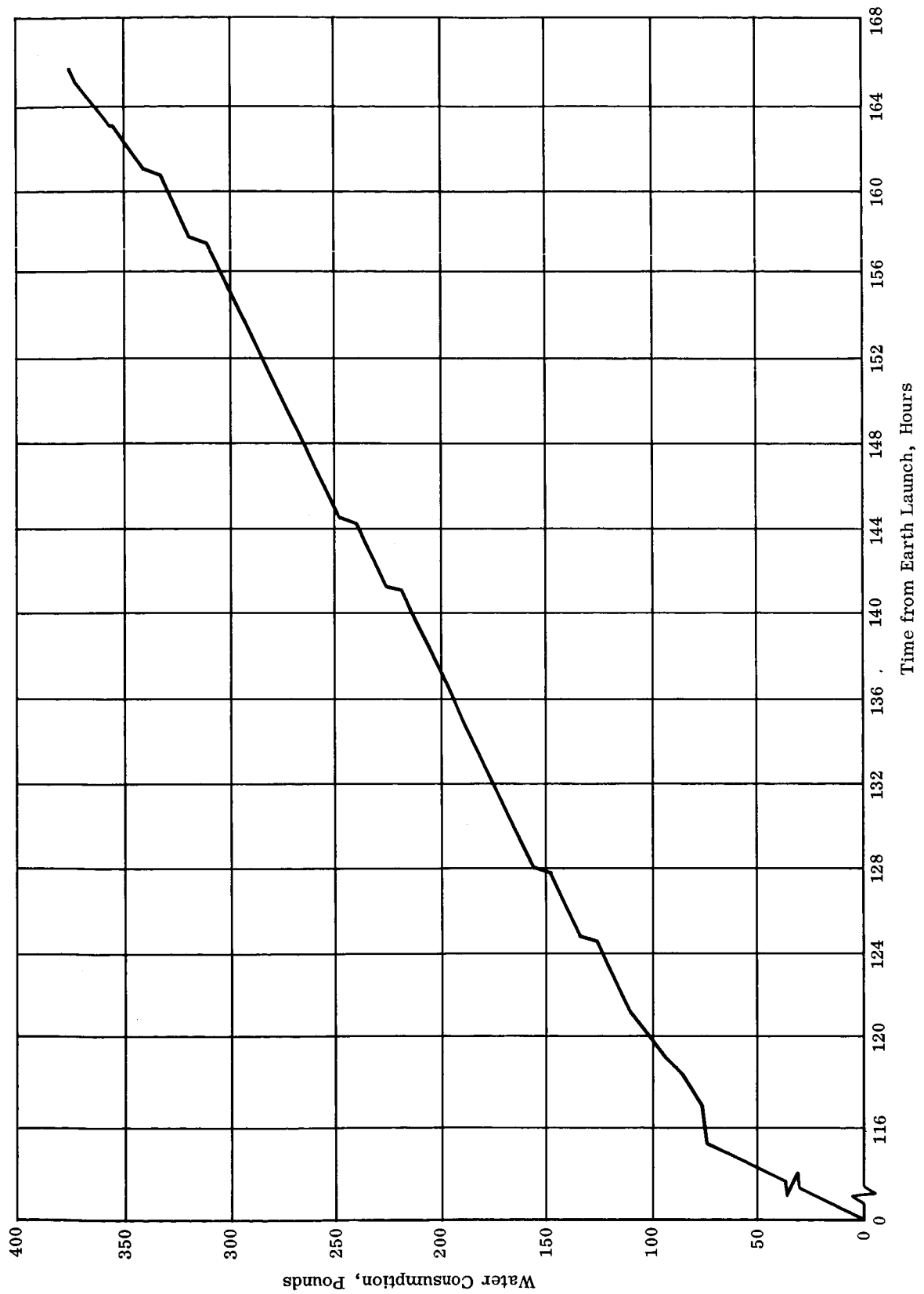


Figure 5 - Water Consumption Profile

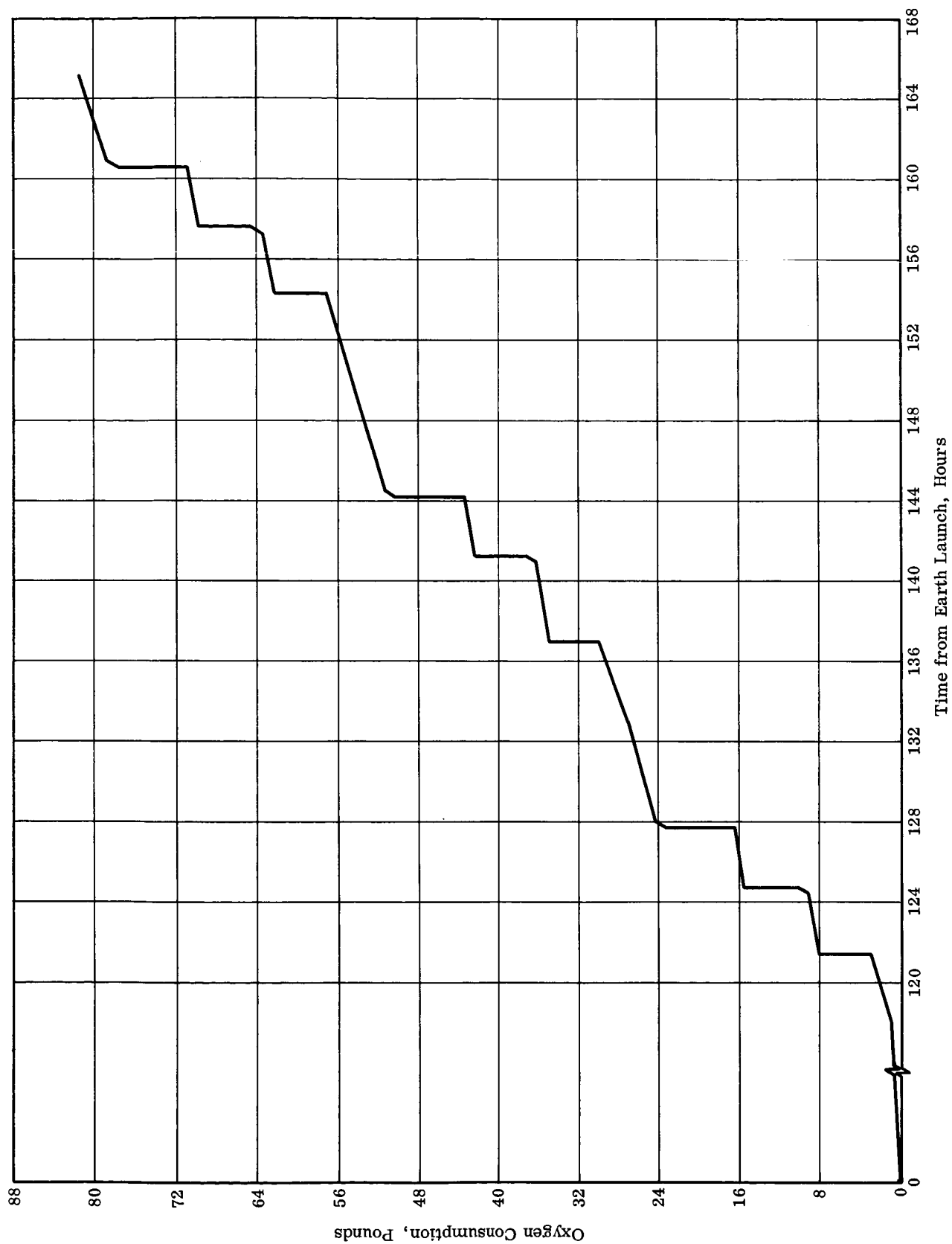


Figure 6 - Oxygen Consumption Profile

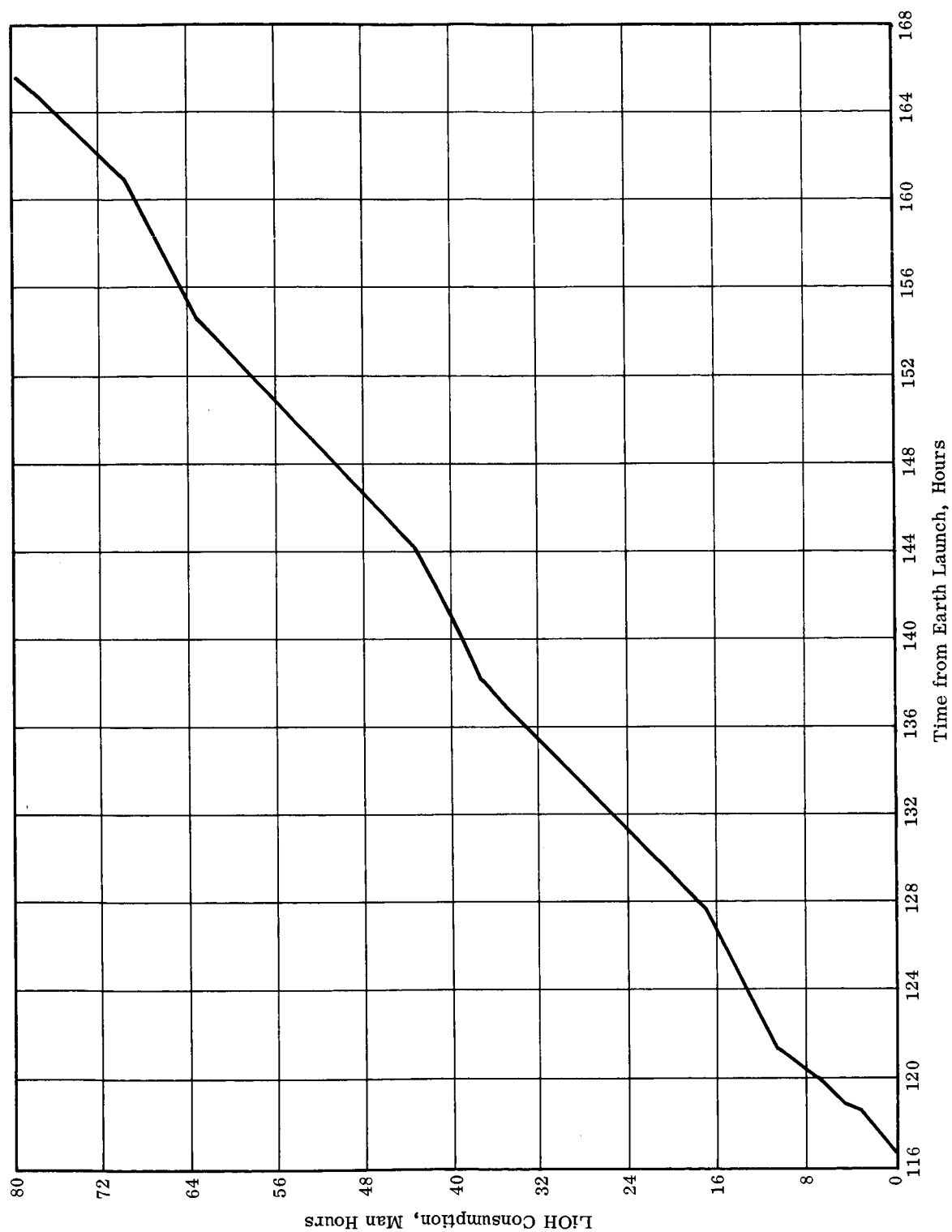


Figure 7 - LiOH Consumption Profile